

Determination of Penetration Depth of Transverse Spin Current in Ferromagnetic Metals by Spin Pumping

Tomohiro Taniguchi^{1,2}, Satoshi Yakata³, Hiroshi Imamura², Yasuo Ando³

¹*Institute for Materials Research, Tohoku University, Sendai 980-8577,*

²*Nanotechnology Research Institute, National Institute of Advanced Industrial Science and Technology, 1-1-1 Umezono, Tsukuba, Ibaraki 305-8568, Japan,*

³*Department of Applied Physics, Graduate School of Engineering, Tohoku University, Sendai*

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Spin pumping in nonmagnetic/ferromagnetic metal multilayers is studied both theoretically and experimentally. We show that the line widths of the ferromagnetic resonance (FMR) spectrum depend on the thickness of the ferromagnetic metal layers, which must not be in resonance with the oscillating magnetic field. We also show that the penetration depths of the transverse spin current in ferromagnetic metals can be determined by analyzing the line widths of their FMR spectra. The obtained penetration depths in NiFe, CoFe and CoFeB were 3.7 [nm], 2.5 [nm] and 12.0 [nm], respectively.

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The field of current-driven magnetization dynamics (CDMD) has drawn enormous attention because of its potential applications to non-volatile magnetic random access memory and microwave devices. CDMD is also important from a scientific point of view since it provides much information about non-equilibrium dynamics of the magnetization and physics of spin transport and spin relaxation. The concept of CDMD was first proposed by Slonczewski [1] and independently by Berger [2] in 1996. In the last decade much effort has been devoted to studying the physics and applications of CDMD both theoretically and experimentally [3, 4].

One of the most important quantities in CDMD is the penetration depth of the transverse spin current λ_t , over which spin transfer torque is exerted for the magnetization of the free layer. However, there is a controversial issue regarding the penetration depth of the transverse spin current. One argument is based on the ballistic theory of electron transport, and its $\lambda_t = \pi/|k_F^\uparrow - k_F^\downarrow|$, which is on the order of the lattice constant in conventional ferromagnets such as Fe, Co, Ni, and their alloys [5, 6]. The other argument is based on the Boltzmann theory of electron transport, and its λ_t is on the order of a few nm [7]. Urazhdin *et al.* analyzed the CPP-GMR of non-collinear magnetic multilayers using the extended two-series-resistance model and concluded that $\lambda_t=0.8$ [nm] for permalloy [8]. On the other hand, Chen *et al.* analyzed the critical current of the CDMD in the Co/Cu/Co trilayer system and concluded that $\lambda_t=3.0$ [nm] for Co [9].

The inverse process of CDMD is spin pumping, where spin current is generated by precession of magnetization in the ferromagnetic layer [10]. Enhancement of the Gilbert damping constant due to spin pumping has been extensively studied, and spin diffusion lengths, i.e., penetration depths of spin current in nonmagnetic metals, have been obtained by analyzing the dependence of the enhancement of the Gilbert damping constant on the thickness of the nonmagnetic metal layer. In spin

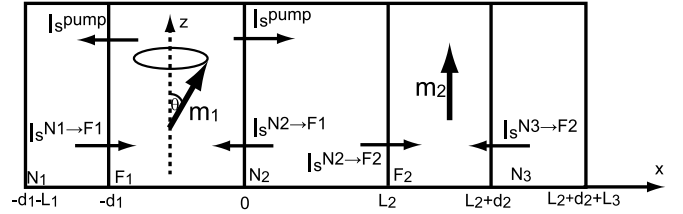


FIG. 1: Schematic illustration of a nonmagnetic/ferromagnetic metal five-layer system. The magnetization of the F_1 layer (\mathbf{m}_1) precesses around the z -axis with angle θ . The magnetization of the F_2 layer (\mathbf{m}_2) is fixed with the z -axis. The precession of the magnetization in the F_1 layer pumps the spin current $\mathbf{I}_s^{\text{pump}}$. The pumped spin current creates spin accumulation in the other layers, and the spin accumulation induces a backflow of spin current $\mathbf{I}_s^{N \rightarrow F}$ across each N/F interface.

pumping, the direction of the magnetization vector of the pumped spin current is perpendicular to the direction of the precessing magnetization vector [10]. Let us consider the nonmagnetic/ferromagnetic metal five-layer system shown in Fig. 1. Since the magnetization vector of the pumped spin current $\mathbf{I}_s^{\text{pump}}$ is perpendicular to the magnetization vector \mathbf{m}_1 of the F_1 layer and the precession angle θ is very small (about 1 [deg]) in conventional FMR experiments, the dominant component of the pumped spin current is perpendicular to the magnetization vector \mathbf{m}_2 of the F_2 layer. Therefore, it would be possible to determine the penetration depth of the transverse spin current in the F_2 layer if we could analyze the dependence of the enhancement of the Gilbert damping constant on the thickness of the F_2 layer.

In this letter, we study spin pumping in $N_1/F_1/N_2/F_2/N_3$ five-layer systems shown in Fig. 1 both theoretically and experimentally. We extend Tserkovnyak's theory of spin pumping by taking into account the finite penetration depth of the transverse spin current and show that the enhancement of the Gilbert damping con-

stant due to spin pumping depends on the ratio of the penetration depth λ_t and the thickness d_2 of the F_2 layer. The motion of the magnetization vector in the F_2 layer is not in resonance with an oscillating magnetic field; hence, the F_2 layer plays the role of spin absorber. We also perform FMR experiments in Cu/CoFe/Cu/Py/Cu, Cu/Py/Cu/CoFe/Cu and Cu/CoFe/Cu/CoFeB/Cu five-layer systems and measure line widths ΔB of energy absorption spectra, which are closely related to the Gilbert damping constants. The abbreviations CoFe, CoFeB, and Py hereafter refer to $\text{Co}_{75}\text{Fe}_{25}$, $(\text{Co}_{50}\text{Fe}_{50})_{80}\text{B}_{20}$ and $\text{Ni}_{80}\text{Fe}_{20}$, respectively. Analyzing the dependence of the line width on the thickness of the Py, CoFe and CoFeB layers that are not in resonance, we showed that the penetration depths of the transverse spin current in the Py, CoFe and CoFeB layers are 3.7 [nm], 2.5 [nm] and 12.0 [nm], respectively.

Let us begin with an introduction to the theory of spin pumping in the nonmagnetic/ferromagnetic metal five-layer system shown in Fig. 1 with a finite penetration depth of the transverse spin current. The pumped spin current generated by precession of the magnetization \mathbf{m}_1 of the F_1 layer is given by

$$\mathbf{I}_s^{\text{pump}} = \frac{\hbar}{4\pi} \left(g_{r(F_1)}^{\uparrow\downarrow} \mathbf{m}_1 \times \frac{d\mathbf{m}_1}{dt} + g_{i(F_1)}^{\uparrow\downarrow} \frac{d\mathbf{m}_1}{dt} \right), \quad (1)$$

where \hbar is the Dirac constant and $g_{r(i)}^{\uparrow\downarrow}$ is the real (imaginary) part of the mixing conductance [10]. The pumped spin current creates spin accumulation in the other layers, and the spin accumulation induces a backflow of spin current across each N/F interface. Although the backflow is obtained from circuit theory [6, 10], the penetration depth of the transverse spin current λ_t is assumed to be zero in this theory. Since we are interested in the effect of the penetration depth of the transverse spin current on spin pumping, we explicitly consider the diffusion process of transverse spin accumulation in the ferromagnetic layer. The backflow of spin current flowing from the N_i layer to the F_k layer is expressed as

$$\begin{aligned} \mathbf{I}_s^{N_i \rightarrow F_k} = & \frac{1}{4\pi} \left[\frac{2g^{\uparrow\uparrow}g^{\downarrow\downarrow}}{g^{\uparrow\uparrow} + g^{\downarrow\downarrow}} \{ \mathbf{m}_k \cdot (\boldsymbol{\mu}_{N_i} - \boldsymbol{\mu}_{F_k}^L) \} \mathbf{m}_k \right. \\ & + g_{r(F_k)}^{\uparrow\downarrow} \mathbf{m}_k \times (\boldsymbol{\mu}_{N_i} \times \mathbf{m}_k) + g_{i(F_k)}^{\uparrow\downarrow} \boldsymbol{\mu}_{N_i} \times \mathbf{m}_k \\ & \left. - t_{r(F_k)}^{\uparrow\downarrow} \mathbf{m}_k \times (\boldsymbol{\mu}_{F_k}^T \times \mathbf{m}_k) - t_{i(F_k)}^{\uparrow\downarrow} \boldsymbol{\mu}_{F_k}^T \times \mathbf{m}_k \right], \quad (2) \end{aligned}$$

where $g^{\uparrow(\downarrow)}$ is the spin up (down) conductance, $t_{r(i)}^{\uparrow\downarrow}$ is the real (imaginary) part of the transmission mixing conductance at the F_k/N_i interface and $\boldsymbol{\mu}_{N_i}$ is the spin accumulation in the N_i layer [6]. The longitudinal spin accumulation in the F_k layer is denoted by $\boldsymbol{\mu}_{F_k}^L$. The last two terms express contributions from transverse spin accumulation $\boldsymbol{\mu}_{F_k}^T$ in the F_k layer.

The spin accumulation in a ferromagnetic layer is defined by the non-equilibrium distribution matrix at a given energy ε , $\hat{f}(\varepsilon) = f_0 \hat{1} + \mathbf{f} \cdot \hat{\boldsymbol{\sigma}}$ [6], where $\mathbf{f} =$

$f_x \mathbf{t}_1 + f_y \mathbf{t}_2 + f_z \mathbf{m}$. Here we introduce the orthogonal unit vectors in spin space ($\mathbf{t}_1, \mathbf{t}_2, \mathbf{m}$). The non-equilibrium charge distribution is represented by $f_0 = (f^\uparrow + f^\downarrow)/2$. On the other hand, $f_z = (f^\uparrow - f^\downarrow)/2$ is the difference in non-equilibrium distribution between spin-up and spin-down electrons, and f_x and f_y are the non-equilibrium distributions of the transverse spin components. The spin accumulation is defined as $\boldsymbol{\mu} = \int_{\varepsilon_F} d\varepsilon \text{Tr}[\hat{\boldsymbol{\sigma}} \hat{f}]$ [10]. The spin accumulation in the nonmagnetic layer is defined in a similar way.

The spin accumulation in a nonmagnetic layer, $\boldsymbol{\mu}_N$, obeys the diffusion equation [11], and is expressed as a linear combination of $\exp(\pm x/\lambda_{\text{sd}(N)})$, where $\lambda_{\text{sd}(N)}$ is the spin diffusion length. The spin current in a nonmagnetic layer is given by

$$\mathbf{I}_s^N = -\frac{\partial}{\partial x} \frac{\hbar S \sigma_N}{2e^2} \boldsymbol{\mu}_N, \quad (3)$$

where S is the cross section area of the system, σ_N is the conductivity and e is the absolute value of the electron charge. The spin current in the N_3 layer is equal to $-\mathbf{I}_s^{N_3 \rightarrow F_2}$ at $x = L_2 + d_2$ because of the continuity of the spin current, and vanishes at $x = L_2 + d_2 + L_3$ (see Fig. 1). Using above boundary conditions, we obtain the spin accumulation in the N_3 layer.

The longitudinal spin current in a ferromagnetic layer is given by

$$(\mathbf{m} \cdot \mathbf{I}_s^F) \mathbf{m} = -\frac{\partial}{\partial x} \frac{\hbar S}{2e^2} (\sigma^\uparrow \mu_F^\uparrow - \sigma^\downarrow \mu_F^\downarrow) \mathbf{m}, \quad (4)$$

where $\mu_F^{\uparrow(\downarrow)} = \int_{\varepsilon_F} d\varepsilon f^{\uparrow(\downarrow)}$ is the electro-chemical potential for the spin-up (spin-down) electrons and $\sigma^{\uparrow(\downarrow)}$ is the conductivity of spin-up (spin-down) electrons. The polarization of spin-dependent conductivity is defined as $\beta = (\sigma^\uparrow - \sigma^\downarrow)/(\sigma^\uparrow + \sigma^\downarrow)$. The longitudinal spin current in the F_2 layer is equal to $\mathbf{m}_2 \cdot \mathbf{I}_s^{N_2 \rightarrow F_2}$ at $x = L_2$ and $-\mathbf{m}_2 \cdot \mathbf{I}_s^{N_3 \rightarrow F_2}$ at $x = L_2 + d_2$ because of the continuity of the spin current. Solving the diffusion equation [11] with the above boundary conditions, we obtain longitudinal spin accumulation in the F_2 layer. The longitudinal spin accumulation is expressed as a linear combination of $\exp(\pm x/\lambda_{\text{sd}(F_L)})$, where $\lambda_{\text{sd}(F_L)}$ is the longitudinal spin diffusion length.

We assume that the transverse spin accumulation obeys the following equation [7]:

$$\frac{\partial^2}{\partial x^2} \boldsymbol{\mu}_F^T = \frac{1}{\lambda_J^2} \boldsymbol{\mu}_F^T \times \mathbf{m} + \frac{1}{\lambda_{\text{sd}(F_T)}^2} \boldsymbol{\mu}_F^T, \quad (5)$$

where $\lambda_J = \sqrt{(D^\uparrow + D^\downarrow)\hbar/(2J)}$ and $\lambda_{\text{sd}(F_T)}$ is the transverse spin diffusion length. Here J represents the strength of the exchange field. The transverse spin accumulation is expressed as a linear combination of $\exp(\pm x/l_+)$ and $\exp(\pm x/l_-)$, where $1/l_\pm = \sqrt{(1/\lambda_{\text{sd}(F_T)}^2) \mp (i/\lambda_J^2)}$. Therefore, we define the penetration depth of the transverse spin current λ_t by

$$\frac{1}{\lambda_t} = \text{Re} \left[\frac{1}{l_+} \right]. \quad (6)$$

The transverse spin current in a ferromagnetic layer is expressed as

$$\mathbf{m} \times (\mathbf{I}_s^F \times \mathbf{m}) = -\frac{\partial}{\partial x} \frac{\hbar S \sigma^{\uparrow\downarrow}}{2e^2} \boldsymbol{\mu}_F^T, \quad (7)$$

where $\sigma^{\uparrow\downarrow} = (1/2)(\sigma^\uparrow/(1+\beta') + \sigma^\downarrow/(1-\beta'))$. Here $\beta' = (D^\uparrow - D^\downarrow)/(D^\uparrow + D^\downarrow)$ is the polarization of the spin-dependent diffusion constants, D^\uparrow and D^\downarrow [7]. For simplicity, we assume that $\beta = \beta'$. The transverse spin accumulation in a ferromagnetic layer is obtained by solving Eq. (5) with boundary conditions satisfying the continuity of the spin current at the N/F interface.

Solving the diffusion equations of the spin accumulations of the N_3 and F_2 layers, the backflow at the N_2/F_2 interface is re-written as

$$\mathbf{I}_s^{N_2 \rightarrow F_2} = \frac{1}{4\pi} \left[g_{(F_2)}^* (\mathbf{m}_2 \cdot \boldsymbol{\mu}_{N_2}) \mathbf{m}_2 + \tilde{g}_{r(F_2)}^{\uparrow\downarrow} \mathbf{m}_2 \times (\boldsymbol{\mu}_{N_2} \times \mathbf{m}_2) + \tilde{g}_{i(F_2)}^{\uparrow\downarrow} \boldsymbol{\mu}_{N_2} \times \mathbf{m}_2 \right], \quad (8)$$

where the conductance $g_{(F_2)}^*$ is given in Ref. [10], and depends on the ratio $d_2/\lambda_{sd(F_L)}$. Similarly, the renormalized mixing conductances, $\tilde{g}_{r,i(F_2)}^{\uparrow\downarrow}$, depend on the ratio $d_2/l_{+(F_2)}$. If the thickness of the N_3 layer is thin enough compared to its spin diffusion length, $\tilde{g}_{r,i(F_2)}^{\uparrow\downarrow}$ are given by

$$\begin{pmatrix} \tilde{g}_{r(F_2)}^{\uparrow\downarrow} \\ \tilde{g}_{i(F_2)}^{\uparrow\downarrow} \end{pmatrix} = \frac{1}{\Delta} \begin{pmatrix} K_1 & K_2 \\ -K_2 & K_1 \end{pmatrix} \begin{pmatrix} g_{r(F_2)}^{\uparrow\downarrow} \\ g_{i(F_2)}^{\uparrow\downarrow} \end{pmatrix}, \quad (9)$$

where $\Delta = K_1^2 + K_2^2$ and K_1 and K_2 are given

$$K_1 = 1 + t_{r(F_2)}^{\uparrow\downarrow} \text{Re} \left[\frac{1}{g_t \tanh(d_2/l_+)} \right] + t_{i(F_2)}^{\uparrow\downarrow} \text{Im} \left[\frac{1}{g_t \tanh(d_2/l_+)} \right], \quad (10)$$

$$K_2 = t_{i(F_2)}^{\uparrow\downarrow} \text{Re} \left[\frac{1}{g_t \tanh(d_2/l_+)} \right] - t_{r(F_2)}^{\uparrow\downarrow} \text{Im} \left[\frac{1}{g_t \tanh(d_2/l_+)} \right], \quad (11)$$

where $g_t/S = \hbar/2e^2\rho_{F_2}l_+$ and ρ_{F_2} is the resistivity of the F_2 layer. The mixing conductance of the F_1 layer in Eqs. (1) and (2) is also replaced by the renormalized conductance.

We assume that spin-flip scattering in the N_2 layer is so weak that we can neglect the spatial variation of the spin current in the N_2 layer. Then we have $\mathbf{I}_s^{\text{pump}} - \mathbf{I}_s^{N_1 \rightarrow F_1} = \mathbf{I}_s^{N_2 \rightarrow F_2}$, and the spin accumulation in the N_2 layer can be determined [10]. The torque acting on the magnetization of the F_1 layer is given by $\mathbf{m}_1 \times \{(\mathbf{I}_s^{\text{pump}} - \mathbf{I}_s^{N_2 \rightarrow F_1}) \times \mathbf{m}_1\}$, which yields the following modified Landau-Lifshitz-Gilbert (LLG) equation [10, 12] :

$$\frac{d\mathbf{m}_1}{dt} = -\gamma_{\text{eff}} \mathbf{m}_1 \times \mathbf{B}_{\text{eff}} + \frac{\gamma_{\text{eff}}}{\gamma} (\alpha_0 + \alpha') \mathbf{m}_1 \times \frac{d\mathbf{m}_1}{dt}, \quad (12)$$

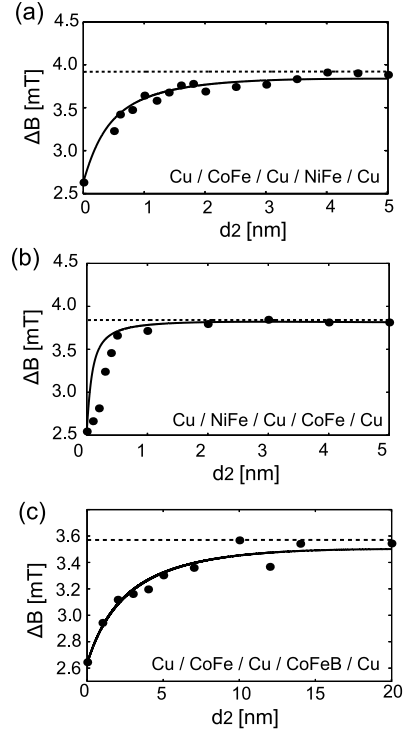


FIG. 2: The dependences of the line width of the FMR power absorption spectra, ΔB , on the thickness of the F_2 layer, d_2 . Materials of the F_2 layer are (a) $\text{Ni}_{80}\text{Fe}_{20}$, (b) $\text{Co}_{75}\text{Fe}_{25}$ and (c) $(\text{Co}_{50}\text{Fe}_{50})_{80}\text{B}_{20}$, respectively. The filled circles represent experimental data and the solid lines are fit to the experimental data according to the theory with the finite penetration depth of the transverse spin current λ_t . The dotted lines represent the case of $\lambda_t = 0$.

where \mathbf{B}_{eff} is the effective magnetic field, γ is the gyromagnetic ratio, α_0 is the Gilbert damping constant intrinsic to the ferromagnetic metal, and α' is the enhancement of the Gilbert damping constant due to spin pumping. The Gilbert damping constant is related to the line width of the FMR absorption spectrum via [13]

$$\Delta B = \Delta B_0 + \frac{2\omega}{\sqrt{3}\gamma} \alpha', \quad (13)$$

where $\omega = 2\pi f$ is the angular velocity of the oscillating magnetic field. We notice that the effects of the N_1 and N_3 layers are quite small because, as mentioned below, the thickness of these layers are thin enough compared to its spin diffusion length in our experiments. Assuming that $g_r^{\uparrow\downarrow} \gg g_i^{\uparrow\downarrow}$ [10], in the limit of $\theta \rightarrow 0$, we find

$$\Delta B - \Delta B_0 \simeq \frac{\hbar\omega}{2\sqrt{3}\pi M d_1 S} \frac{\tilde{g}_{r(F_1)}^{\uparrow\downarrow} \tilde{g}_{r(F_2)}^{\uparrow\downarrow}}{\tilde{g}_{r(F_1)}^{\uparrow\downarrow} + \tilde{g}_{r(F_2)}^{\uparrow\downarrow}}, \quad (14)$$

where $\tilde{g}_{r(F_i)}^{\uparrow\downarrow}$ ($i = 1, 2$) is the real part of the renormalized mixing conductance of the i -th ferromagnetic layer. We should note that if we neglect the transverse spin accumulation in the ferromagnetic layer the mixing conductances are not renormalized, and that the line width

ΔB does not depend on the thickness of the F_2 layer [10]. This is due to the fact that the dominant component of the pumped spin current is perpendicular to the magnetization vector \mathbf{m}_2 of the F_2 layer in our experiment.

We performed FMR experiments on the three different $N_1/F_1/N_2/F_2/N_3$ five-layer systems shown in Fig. 1 [14]. Nonmagnetic layers are made of Cu. The combinations of the ferromagnetic layers (F_1, F_2) of each system are (a) (CoFe, Py), (b) (Py, CoFe) and (c) (CoFe, CoFeB). The samples were deposited on Corning 1737 glass substrates using an rf magnetron sputtering system in an ultrahigh vacuum below 4×10^{-6} [Pa] and cut to 5 [mm²]. The Ar pressure during deposition was 0.077 [Pa]. The thickness of all Cu layers are 5 [nm]. The thickness of F_1 layers is 5 [nm] for sample (a) and (b), and 10 [nm] for sample (c). The FMR measurements were carried out using an X-band microwave source ($f = 9.4$ [GHz]) at room temperature. The microwave power, modulation frequency, and modulation field are 1 [mW], 10 [kHz], and 0.1 [mT], respectively. The precession angles of all samples are estimated to be 1 [deg]. The resistivity ρ_F of Py, CoFe and CoFeB are 241 [Ω nm], 94 [Ω nm] and 1252 [Ω nm], respectively. The magnetizations ($4\pi M$) of Py and CoFe are 0.76 [T] and 2.1 [T], respectively. The gyromagnetic ratio is 1.8467×10^{11} [Hz/T] for all systems.

In Figs. 2 (a), (b) and (c), the measured line widths of the FMR absorption spectra ΔB are plotted with filled circles against the thickness of the F_2 layer, d_2 . The solid lines are fit to the experimental data according to the theory with the finite penetration depth of the transverse spin current λ_t . The dotted lines represent the calculated ΔB in the case of $\lambda_t = 0$ [10].

Parameters other than λ_t are determined as follows. The mixing conductances per unit area of the combinations ($g_{r(F_1)}^\uparrow/S$, $g_{r(F_2)}^\uparrow/S$) are assumed to be (a) (48.0, 38.0), (b) (15.2, 17.0) and (c) (48.0, 128.0) [nm⁻²]. Although these values are determined by fitting, they have

good agreement with the *ab initio* calculations [6]. For simplicity, we assume that $t_r^\uparrow = t_i^\uparrow$ where values of $t_{r,i}^\uparrow/S$ of Py, CoFe and CoFeB are taken to be 4.0 [nm⁻²], 6.0 [nm⁻²] and 0.8 [nm⁻²], respectively. The longitudinal spin diffusion lengths are 5.5 [nm] for Py and 12 [nm] for CoFe and CoFeB, respectively [15, 16]. The polarizations of conductance β are 0.73 for Py, 0.65 for CoFe and 0.56 for CoFeB, respectively [15, 16, 17]. The transverse spin diffusion lengths are given by $\lambda_{sd(F_T)} = \lambda_{sd(F_L)}/\sqrt{1-\beta^2}$ [7]. We take $g_i^\uparrow/S = 1.0$ [nm⁻²], $2g^\uparrow g^\downarrow/(g^\uparrow + g^\downarrow)S = 20.0$ [nm⁻²] [6, 10] for all systems; these are not important parameters for fitting the experimental results. The spin diffusion length and resistivity of Cu are taken to be 500 [nm] and 21 [Ω nm] [18]. The obtained values of λ_t are 3.7 [nm] for Py, 2.5 [nm] for CoFe and 12.0 [nm] for CoFeB, respectively. Our results agree quite well with the prediction based on the Boltzmann theory of electron transport [7].

In conclusion, we analyzed spin pumping in Cu/CoFe/Cu/Py/Cu, Cu/Py/Cu/CoFe/Cu and Cu/CoFe/Cu/CoFeB/Cu five-layer systems both theoretically and experimentally. We showed that the enhancement of the Gilbert damping constant due to spin pumping depends on the ratio of the penetration depth λ_t and the thickness of the ferromagnetic layers, which is not in resonance with the oscillating magnetic field. We measured the line widths of FMR absorption spectra, which are closely related to the Gilbert damping constant. Analyzing the experimental results, we showed that the penetration depths of the transverse spin current in Py, CoFe and CoFeB are 3.7 [nm], 2.5 [nm] and 12.0 [nm], respectively. Our results support the Boltzmann theory of transverse spin current [7].

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